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Research Progress in 3D Printing Technology for Optoelectronic Devices

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Abstract. In recent years, photoelectric devices have seen increasingly profound applications in critical fields such as display technologies, energy systems, and advanced manufacturing. Their technological advancement and performance optimization have become central driving forces in promoting the upgrading of related industries. Leveraging its prominent characteristics, such as high design flexibility, rapid prototyping capabilities, and customizable fabrication of complex structures, 3D printing technology demonstrates unique technical advantages in the field of optoelectronic device manufacturing. This paper systematically reviews the application progress of 3D printing technology in the field of photoelectric devices, including display devices, solar cells, and photodetectors. In addition, the specific application practice and technical breakthrough in the display core devices, such as light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs), are mainly described. In the future, 3D printing technology will play an important role in the field of optoelectronic devices. Specifically for core display components, it enables more efficient and cost-effective production, thereby driving advancements in display technology toward higher resolution and miniaturization. 3D printing will also bring breakthroughs in improving the efficiency of solar cells and the integration of photodetectors.

Keywords: 3D printing, optoelectronic devices, display devices

1. Introduction

Amidst the global wave of technological innovation and industrial upgrading, photoelectric devices have progressively emerged as a critical enabling technology for sustainable development in modern society. From display terminals to solar cells and photoelectric sensors, the performance optimization and functional expansion of optoelectronic devices have posed brand-new challenges to manufacturing technology. Traditional manufacturing methods have significant limitations in complex structure construction, material utilization, and personalized customization. For instance, it is difficult to realize the bionic hierarchical structure in plane processing, and the high-temperature process is easy to lead to the degradation of the performance of optoelectronic materials, which seriously restricts the development of optoelectronic devices in the direction of high integration and multifunction [1, 2].

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As a revolutionary additive manufacturing method, 3D printing technology has opened up a new path for the preparation of optoelectronic devices with its unique advantages of digital driving, free forming of complex structures, and multi-material collaborative printing. In contrast to traditional subtractive manufacturing, 3D printing can not only realize the accurate preparation of precision structures, but also significantly improve the photoelectric performance of devices through material gradient design and bionic shape control [3, 4]. In recent years, research on the application of this technology in the field of optoelectronic devices has achieved significant progress. In the field of display technology, quantum dot light-emitting diodes (QD-LEDs) and flexible organic light-emitting diodes (OLEDs) have enabled full-color dynamic displays for wearable devices through the application of inkjet and extrusion hybrid printing techniques [5-7]. In the field of energy, 3D-printed graphene-TiO_2 photoanodes with hierarchical channel structures have significantly enhanced the efficiency of photo fuel cells driven by seawater pollutants [4]. In the photovoltaic field, the external light trap design increases the short-circuit current density of nanocrystalline silicon solar cells by 14% through a 3D printing concentrator [2, 8]. In the field of sensing technology, photodetectors fabricated via 3D printing exhibit robust mechanical properties and demonstrate applicability in human ultraviolet radiation detection, thereby contributing to healthcare advancements [9, 10].

Although 3D printing of optoelectronic devices has demonstrated great potential in material innovation and functional integration (such as photodetector-LED composite devices), it still faces challenges such as the trade-off between printing accuracy and device stability, as well as the regulation of interface compatibility among multiple materials [9]. Based on the above research progress, this paper systematically reviews the application status of 3D printing technology in the field of optoelectronic devices, focusing on its technological breakthroughs in the core directions of sensing, display, energy conversion, and so on. It aims to further promote the development of 3D printing technology and realize the application of 3D printing technology in multiple scenes.

2. Overview of 3D printing technology and optoelectronic devices

3D printing technology is a digital manufacturing technology that builds 3D objects by stacking materials (plastic, metal, ceramics, biological materials, etc.) layer by layer. Currently, it is divided into Fused Deposition Modeling (FDM), Stereolithography (SLA)/Digital Light Processing (DLP), Selective Laser Sintering (SLS), etc. The advantages, disadvantages, and underlying principles of specific 3D printing technologies are detailed in Table 1.

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Table 1. Advantages, disadvantages, and principles of 3D printing technology

Name	Principle	Advantages	Disadvantages
FDM	The molten thermoplastic material is extruded layer by layer through a heated nozzle and subsequently solidified via cooling to form the final structure.	Low equipment cost; Rich variety of materials; Low environmental requirements.	Low precision; Slow printing speed.
SLA	The ultraviolet laser is focused onto the surface of photosensitive resin, solidifying the resin layer by layer to achieve formation.	High precision; Strong detail representation.	The material is highly brittle. Post-processing is required, and the printing size is limited by the resin tank.
SLS	Laser selective sintering of powder materials, the powder itself melts and bonds to form a shape.	The material has high strength. It can be used to print functional parts.	The surface has a granular texture; there are few material options (mainly nylon and modified materials), and a sealed environment is required to prevent powder from flying around.

Optoelectronic devices are semiconductor components that primarily utilize the mutual conversion between light and electricity. As the cornerstone of optoelectronic technology, it underpins critical domains including information transmission, energy conversion, and sensing detection. The physical foundations encompass phenomena such as the photoelectric effect, photoluminescence, and electro-optic effects. These include the conversion of electrical signals into optical signals (e.g., light-emitting devices), the transformation of optical signals into electrical signals (e.g., photosensitive sensors), and optical transmission/modulation components, as detailed in Table 2. In manufacturing, 3D printing technology is used to further enhance the flexibility of optoelectronic device customization, expand the application range of optoelectronic devices, and improve the performance of optoelectronic devices.

Table 2. Types and functions of optoelectronic devices

Types	Functions	Specific device
Light source device	Generation of optical signals	Light Emitting Diode (LED), Organic Light Emitting Diode (OLED).
Photodetection device	The conversion of optical signals into electrical signals.	Photodiode (PD).
Optical modulation device	Modulation of optical signal parameters, including intensity, frequency, and phase.	Photomultiplier Tube (PMT).

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3. Application of 3D printing in optoelectronic devices

3.1. 3D printing display device

At present, the most commonly utilized display technologies include OLED, LED and QD-LED, among others. Kong et al. studied 3D printing QD-LED at an earlier stage. By formulating different printing strategies, a variety of materials were stacked to achieve all 3D printing of QD-LED [5]. The 3D printing used here is more traditional extrusion 3D printing. In 2020, Eder et al. conducted research on printed OLEDs, replacing the traditional glass substrate with transparent ultraviolet-curable resin and the anode with a conductive layer composed of PSS (poly(3,4-ethylenedioxythiophene)), and achieved OLED luminescence through inkjet printing [11]. Su et al. further advanced the optimization of the active layer through inkjet printing technology, significantly enhancing the uniformity of the spray-printed active layer. By selecting MDMO-PPV as the luminescent material, they achieved an emission peak at 574 nm. Additionally, the mechanical stability of the 3D-printed OLED devices under bending conditions was experimentally evaluated [6].

Although some achievements have been made in 3D printing display devices, and 3D printing of QD-LED and OLED has been realized, in practice, due to the high printing threshold, such as the metal cathode is easy to oxidize, the contact area is limited when using inkjet printing directly, the active layer may be damaged during UV curing, the difference between different samples is large, the nozzle is easy to be blocked, and the printing environment is strict, it still cannot be widely promoted.

3.2. 3D printing solar cells

Due to the importance of environmental protection in recent years, solar cells have made great progress in different aspects. In 2022, Dinesh et al. 3D designed and printed a photoelectrochemical cell for the evaluation of photoanodes [2]. Previously, the absence of standardized metrics for the optoelectronic properties of materials precluded meaningful comparative analysis [2]. By comparing the synthesis methods of BiVO4 and the two preparation methods of photoanodes, they found the best method for preparing photoanodes. Moreover, they discovered that different synthesis methods had little impact on the results when measuring the photocatalytic activity of this photoelectrochemical cell, which is conducive to standardizing the photocurrent measurement among different photoelectric materials and enables different studies to be reused [2]. Yang et al. Prepared graphite oxide solution by improved Hummer method and mixed it with anatase TiO2 nanoparticles to prepare go uniform TiO2 ink with a mass fraction of 10%-40%. With 3D printing photoanode as the core, it was combined with Au PVDF cathode (magnetron sputtered Au modified PVDF fiber) and PVDF separator to form a three-layer structure of photoanode, separator cathode to realize a self-floating design [4]. The self-floating design renders it suitable for marine environments, enabling efficient degradation of hydrocarbons and other pollutants while simultaneously generating electricity. Hydrocarbons with shorter carbon chains exhibit photocurrent densities exceeding 0.49 mW cm^{-2}, demonstrating the potential of 3D-printed photocatalytic fuel cell (PFC) systems for electricity generation from seawater pollutants. This highlights its promising applications in environmental protection and energy development [4].

The Di Vece team studied how to realize flexible and stretchable connections through 3D printing silver microelectrodes and ITO microelectrode [11]. When both were used for interconnection in perovskite solar cells, the module efficiency reached 4.6%, further enhancing the efficiency of solar

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cells [11]. Furthermore, the inkjet-printed perovskite layer (tri-cation system) achieved a power conversion efficiency of 12.9% with improved stability. The team also designed 3D-printed external light-trapping structures, which enhanced the short-circuit current density of 1.2 μm thick nc-Si: H solar cells by 14%, increased the maximum power point current by 15%, and extended the optical path length in the long-wavelength region by a factor of 1.5–2.5 [11]. The above research shows the potential of 3D printing technology in improving the efficiency of solar cells and reducing costs. With the further application of 3D printing technology, the photoelectric chemical cell can be used to establish a unified standard for the photoelectric properties of materials, and to conduct research on different photoelectric materials. In addition, the structure of the solar cell is directly optimized, including the improvement of the solar cathode and anode, and the 3D printing of external light traps, so as to realize the power generation using pollutants and improve the efficiency of the solar cell.

3.3. 3D printing photodetector

Traditional photodetectors have limitations such as poor flexibility, a single structure, and a manufacturing process that relies on clean rooms. With 3D printing manufacturing, the flexibility of the detectors can be enhanced, and the reliance on clean rooms can be eliminated. Park et al. used extrusion 3D printing technology to realize multi-material layer-by-layer deposition by controlling nozzle size (100 μ m), extrusion pressure (0.1-105 psi), and printing speed (0.2-5 mm/s), thus realizing the preparation of high-performance polymer photodetectors [9]. Under the excitation of an LED pulse light (10 V, 0.8 Hz), the photodetector produces the same frequency photocurrent response, which verifies the effectiveness of optical coupling. It has laid a foundation for the more flexible application of photoelectric detectors in the future [9]. In 2022, Xia et al. achieved 3D printing of ultraviolet to visible light band photodetectors, which were applied to detect the skin environment of patients [10]. They incorporated zinc oxide (ZnO) as a dopant into the organic active material for ultraviolet absorption, utilizing UV-ozone-treated polydimethylsiloxane (PDMS) as the substrate and PSS as the detector [10]. The optimized photodetector ultimately exhibited an external quantum efficiency (EQE) exceeding 100% at a wavelength of 310 nm, with performance comparable to that of commercial silicon-based detectors [10]. These findings demonstrate that 3D-printed photodetectors possess excellent flexibility and tensile properties, making them suitable for wearable devices. Future enhancements may be achieved by improving detection performance and expanding the detection range—for instance, by extending coverage to the far-infrared spectrum.

4. Discussion

3D printing has successfully achieved direct printing of QD-LED and flexible OLED in the field of display devices, promoting the technological innovation of wearable/foldable displays. In energy conversion devices, by 3D printing hierarchical channel graphene-TiO_2 photoanodes, vertically oriented graphene fuel cells, and external light trap structures, the light capture efficiency and energy conversion performance have been significantly enhanced [4]. In terms of sensing and detecting devices, high-performance photodetectors were developed, and flexible photodetectors were printed and applied to detect the skin environment. The application of 3D printing technology in optoelectronic equipment has made great progress.

However, the technology still faces many challenges. Nano-scale printing is difficult to take into account mass production speed and economy, and cannot be directly and widely used. When inorganic/organic and rigid/flexible materials are used for collaborative printing, the interface is not

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stable enough and prone to fracture. Organic semiconductors are vulnerable to environmental erosion, resulting in device damage, and packaging technology needs to be improved. For example, FDM technology, which is commonly used at present, may cause printing failure when materials cannot be attached to the surface during printing.

For fine printing, it can be achieved by enhancing the precision of the nozzle. As for organic semiconductors being affected by the environment, solutions such as filling rare gases during the 3D printing process to isolate them from the external environment can be adopted to expand the application scope and durability of 3D printing.

In the future, optoelectronic devices are expected to promote large-scale applications of high-performance, low-cost, and customized optoelectronic devices through 3D printing technology.

5. Conclusion

This paper provides a systematic review of the research progress and application potential of 3D printing technology in the field of optoelectronic device manufacturing. Research shows that compared with traditional manufacturing processes, 3D printing, with its core advantages of high freedom in digital design, precise construction of complex three-dimensional structures, and strong ability to form multiple materials in coordination, provides a revolutionary solution for the development of optoelectronic devices towards higher integration, flexibility, functionality, and personalization. In recent years, 3D printing has made significant progress in the manufacturing of optoelectronic devices. In the display field, 3D-printed OLED screens can achieve flexible displays and have good mechanical properties. In the energy field, 3D-printed solar cells have a higher photoelectric conversion rate, can be used to treat marine pollutants, and generate electricity. In the photoelectric detection field, 3D-printed photodetectors have better flexibility and can be used to detect the surrounding environment of the human body. However, the precision of Fused Deposition Modeling (FDM), the mainstream 3D printing technology, is insufficient for fabricating micron-scale optoelectronic structures. The anisotropic mechanical strength between the vertical and horizontal directions can easily lead to interlayer delamination during the bending of flexible optoelectronic devices, thereby compromising circuit conductivity. Challenges related to precision and material properties still require progressive breakthroughs through technological optimization and material innovation.

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